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Vulnerability of buildings to windstorms and insurance loss estimation

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Abstract

Windstorms cause enormous loss to life and property worldwide. Insurance companies use risk assessment models to assess the financial risk to their insurance exposure due to windstorms. The estimation of the intensity of hazard and the vulnerability of buildings to windstorms are important parts of a windstorm risk assessment model. The vulnerability functions (or curves) are, in general, based on analyses of loss data from insurance companies. The loss data available from insurance companies following a natural disaster is generally comprised of losses representative of a wide variety of buildings, often lacking information on building-specific characteristics such as height and material. Analysis of such data may not go beyond the development of an aggregate (or generic) vulnerability curve for a combined portfolio giving no idea of the vulnerability of individual building types represented by this curve. The paper discusses the vulnerability of buildings to windstorms and the development of vulnerability functions for windstorm loss estimation. A methodology is presented for the disaggregation of a generic vulnerability curve into several curves representing individual building types. The methodology provides a convenient way of translating known vulnerabilities for a region to those for another region by combining them with actuarial data and building inventory information of the region. The methodology is applied for the disaggregation of generic vulnerability curves for the Caribbean Island of Puerto Rico. The hurricane hazards and the consequent property losses in the region are also discussed.

Keywords: Hurricanes; Damage; Insurance; Risk assessment; Vulnerability; Wind

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1. Introduction

Every year severe windstorms ravage regions in the Atlantic, Indian and Pacific Oceans. Hurricane Andrew in 1992, with total economic losses estimated at $30 billion [1] is labeled as one of the costliest natural disasters in the history of the United States of America. Hurricane Georges in 1998 caused insured losses of about $3.5 billion in the USA and the Caribbean [2] and Hurricane Floyd in 1999 caused insured losses of $1.96 billion in the USA [3]. Thousands of people lost their lives in the "Super Cyclone" 05B that struck coastal India in October 1999. The insured losses in the December 1999 European windstorms Lothar and Martin have been estimated at $5.8 billion and $2.4 billion, respectively [4]. These figures show the serious implications of wind-related catastrophes to both life and property.

The assessment of the economic impact of windstorms requires knowledge of the meteorological aspects of wind as well as the property effected. Emergency managers, fiscal policy planners, government and the industry use windstorm loss and risk assessment models to study the effects of severe winds at local or regional levels. Insurance is the primary mechanism used by industrialized countries to manage the risks associated with windstorms. Insurance companies use risk assessment models to assess the financial risk to their insurance exposure due to windstorms. A windstorms risk assessment model is comprised of four basic modules: hazard, exposure, vulnerability and loss. The hazard module is a representation of the physical event itself and determines the intensity of the hazard, for instance, the wind speeds. The exposure module describes the specific geographic and structural attributes of properties. The vulnerability module, through the application of vulnerability functions, establishes the relationship between the hazard and the consequent physical damage or an estimate of the cost to repair the damage. The loss module computes the economic losses for a given insurance exposure, taking into account specific coverage terms like limits and deductibles etc.

The main focus of this paper is to describe the assessment of vulnerability of buildings to windstorms. The many imponderables involved in defining the wind vulnerability of buildings like wind speed, wind direction, storm duration, building size and geometry, roof shape, terrain conditions, shielding by surrounding structures, construction quality, building codes and their implementation, etc., make the task of quantifying vulnerability very complex. Since windstorms are covered in various property insurance policies, they remain a significant concern of insurance and reinsurance purchasers and providers. Thus, the insurance industry, with help from catastrophe modelers, has been on the forefront of examining the impact of severe winds on property, and routinely performs analysis of the wind-induced economic losses to insurance portfolios for developing vulnerability models. However, because of the proprietary nature of such data, the details of such efforts are not readily available in the public domain. Windspeed-damage relationships based on statistical analysis of limited insurance claims data are described in [5,6]. While multivariate regressions on loss data would normally be used for developing vulnerability functions, the dearth of data has forced researchers to look for alternative methods for example, basing vulnerability models on logical hypotheses [7].

The development of windstorm loss assessment models, for many markets outside the US, particularly for less industrialized countries, with low insurance penetration, is still at a preliminary stage. The obvious reason for this, ironically, is the absence of major insurance losses, since the early nineties, on which to develop and calibrate the models as well as to determine their trustworthiness. Even where insurance loss data are available, it is generally in the form of overall losses, i.e. losses aggregated over many different types of buildings in a region. Sometimes the losses may be available in terms of various occupancies, i.e. residential or commercial etc., but rarely, in the past, has actuarial data provided an insight into other crucial details pertaining to the composition of the building stock or class, like the building material, height etc. Although, this may present an overall picture of losses, it does not offer a view of the losses in terms of specific building types (or classes). Thus, the problems of developing building class specific vulnerability curves, as well as the assessment of vulnerability of properties to windstorms for regions with no available loss data remain.

The paper discusses the vulnerability of buildings to windstorms and the development of vulnerability functions for hurricane loss estimation. A methodology is presented for the translation of known building vulnerability curves of a region, where detailed loss data are available, to another region with less data, by combining them with limited actuarial data and building inventory information of the region. The methodology can be used to disaggregate a generic vulnerability curve into several curves representing vulnerability of specific building classes. The developed vulnerability curves are finally combined with the hurricane windfield and the insurance exposure to estimate the insurance losses in Puerto Rico.

2. Development of vulnerability functions

The vulnerability to windstorms, of a portfolio of buildings, is expressed by "vulnerability functions", also known as vulnerability curves or damage curves. Windstorm vulnerability functions represent the relationship between windspeed and the "mean damage ratio" (MDR). The MDR, D_v, at windspeed v, is defined as

$$D_v = \frac{\sum_{i=1}^{n} L_i}{\sum_{i=1}^{n} V_i}, \quad (1)$$

where L_i is the cost to repair the damage, or the loss, to buildings at location i, V_i is the total value of buildings at that location and n is the total number of locations experiencing windspeed v. The damage is expressed as a percentage of the total value of the building and represents the vulnerability of a building to wind, a high MDR signifying higher vulnerability.

The two principal prerequisites for developing windstorm vulnerability functions are the financial loss data and the wind field. In addition to the above, information on the building damage statistics, knowledge of wind-structure interaction, building code information as well as a knowledge of the socio-economic conditions of the region all contribute to the development of a sound vulnerability model.

For each location, typical claims data may consist of the total insured value, limit, deductible and loss. The claims data may differentiate between losses to building, contents and business interruption, as well as may be split by lines of business (e.g., residential, commercial etc.) and sometime by type of construction (e.g., woodframe, masonry, etc.). When preparing claims data for analysis, it is important to understand how the limits and deductibles are considered in calculating the total insured value of the property and the losses paid (net of deductibles) as opposed to the actual losses suffered. The next step is to obtain windspeeds for the region under consideration and correlate them to each location for which claims data are available. It is not practically feasible to obtain observed windspeeds for each location under consideration. Thus, windfield models that consider the meteorological characteristics of a storm coupled with site characteristics like ground roughness, topography, etc., are used to calculate windspeeds at locations of interest. The windfield models are also calibrated with limited observed data. Thus, for each location (say, postal code) in the insurance claims file, the windspeed can be obtained from the windfield model.

The claims data are divided into various windspeed ranges, (say 10 kph) in ascending order of windspeeds and a MDR and average windspeed is calculated for each range using Eq. (1). Finally, the data are regressed to obtain a relationship between windspeed and MDR for a given windstorm. Fig. 1 shows the results of analyses performed on a sample set of insurance loss data for Hurricane Andrew in

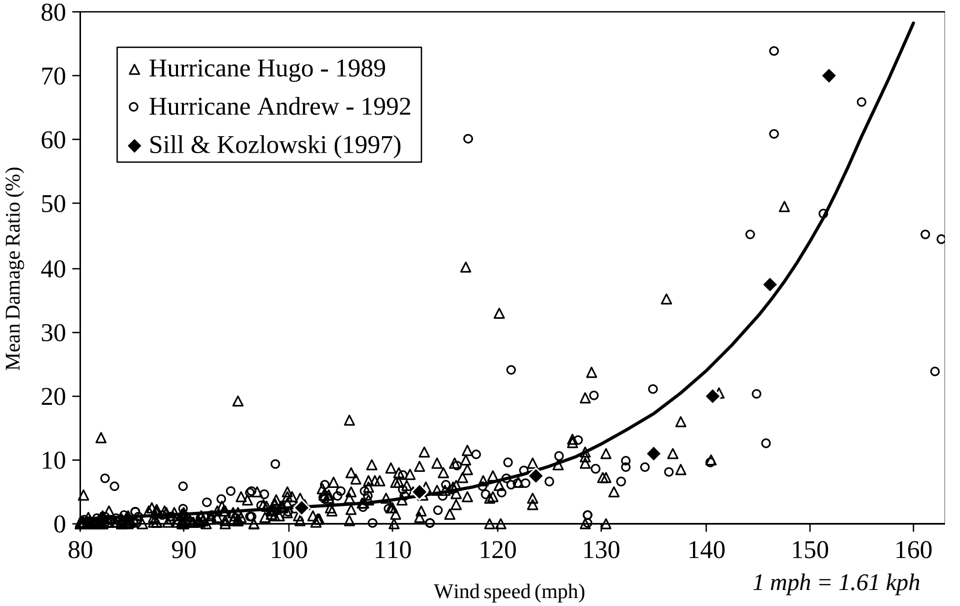

Fig. 1. Typical hurricane vulnerability curve for wood frame buildings.

1992, for wood frame residential buildings, constituting a total loss of about $43 million. The data points for losses in South Carolina during Hurricane Hugo in 1989 are also shown. The windspeed is 3-s peak gust at 10 m height. Note that the vulnerability curve shown is aggregate in nature, and could be refined for additional parameters affecting damage, such as upstream exposure, distance to coast, roof type, etc. Also shown in the figure are comparisons with the damage ratios, based on logical hypotheses, suggested by Sill and Kozlowski [7] which show a good match with the curve for windspeeds up to 125 mph, but diverge at higher windspeeds, suggesting a steep increase in damage ratios at windspeeds above 135 mph. It should be noted that this curve is representative of a single event—Hurricane Andrew; the desired curve used in loss assessment models, however, is calibrated using observed losses from several storms.

3. Overall vs. building class specific losses

Analysis of actuarial data from insurance companies is currently the main building block in the development of vulnerability functions. In absence of detailed loss data, companies have to rely on estimates based on aggregate losses for a portfolio of buildings. While portfolio-wide loss estimates may present an overall picture of losses aggregated over many different types of buildings in a region, they do not offer a view of the losses in terms of building classes. The insurance companies may require building class specific vulnerability functions for judging relative risk in underwriting practices. This is true, especially for insurers who insure unique sets of risks such as hotels or high rise buildings so their inventory is not "typical", for developing reasonable insurance rates. This is opposed to developing region-wide loss estimates where the details of building class specific losses are not as critical. Since loss data may not be available at a finer resolution than say, occupancy (residential or commercial) or material (wood or masonry) levels, the big question is how to go about developing vulnerability function for each of the several types of buildings present in a company's portfolio? The basic variables that define a class of buildings are

(a) occupancy: residential, commercial, industrial, etc.,
(b) construction material: wood, masonry, reinforced concrete, steel, etc., and
(c) height: low-rise, mid-rise and high-rise.

This classification can create several combinations representing various possible building classes. To conduct a detailed analysis of a building portfolio, vulnerability curves for individual building classes are required. However, in absence of detailed financial loss data, developing individual vulnerability curves for such a diverse set of building classes poses a major challenge to model developers.

The splitting of a generic vulnerability curve into its component curves requires a knowledge of the relative vulnerabilities of various building classes that comprise the generic curve. On a broad level, in absence of detailed data, a generic curve may be split into its basic components by several methods: (a) by applying engineering principles, judgment and logical assumptions—for instance, a wood frame building, in a hurricane, is more vulnerable than say, a reinforced concrete building; (b) by using observations of post-event damage surveys and (c) by analyzing limited loss data to support the relative vulnerability of buildings. The main limitation of this approach lies in its subjectivity. Although it is not possible to do away with the subjective component, the following approach presents a logical and objective methodology for generating individual curves from a generic vulnerability curve.

Fig. 2 shows a set of typical vulnerability curves, C_1 to C_n, each representing wind-induced damage to a specific class of buildings from 1 to n. The MDR at wind speed v is given by D_1 for building class 1 and D_n for building class n. The generic building curve that incorporates the vulnerability characteristics of all building classes is shown by curve C_g, with MDR D_g at velocity v. In general, due to the aggregate nature of the loss data, only a typical vulnerability curve C_g (say, for commercial buildings) can be derived. The development of curves for various other building classes within the general commercial class are left to the engineering judgment of the designer. Thus, the disaggregation of the generic vulnerability curve C_g remains a problem.

The MDR, D_g for the generic curve can be expressed as a sum of the MDRs of each contributing building class, weighted by the percentage (w) of such buildings present in the given region, as follows:

$$D_g = \frac{\sum_{i=1}^{n} D_i w_i}{\sum_{i=1}^{n} w_i}, \tag{2}$$

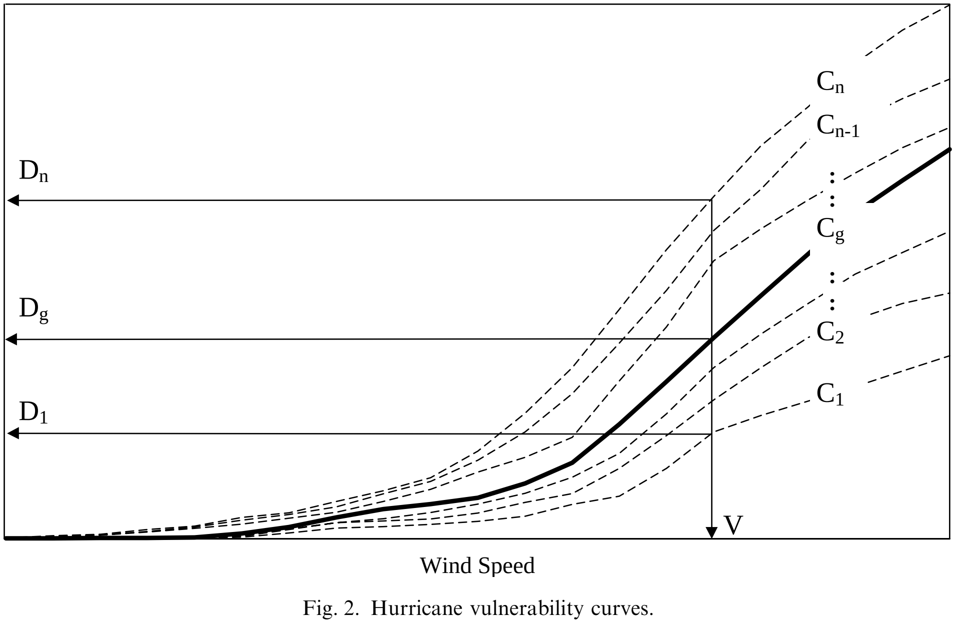

Fig. 2. Hurricane vulnerability curves.

where D_i is the MDR at a given velocity, for the ith building class; w_i is the percentage of buildings of class i, and n is the total number of building classes. The answer to the disaggregation problem lies in the solution of Eq. (1), which represents a system with n unknowns represented as D_i. For solving this equation, the following assumptions are made:

(a) a set of vulnerability curves, for another region or country, that could be used as benchmark curves, is available, and
(b) the relative vulnerabilities among different building classes are the same across different regions or countries.

It is thus assumed that the ratio of MDRs at a given wind speed for, say, a reinforced concrete building is constant for two different regions. Note that reasonability of this type of assumption has to be considered on a building class by building class basis due to differences in design and construction practices and adjustments made as necessary. For example, low rise concrete or masonry residential buildings are built differently in Puerto Rico and the US.

Thus, for known vulnerability curves (say for country X), the ratios k_1 to k_n, of MDRs for curves C_1 to C_n (see Fig. 2), respectively, and a reference curve C_r can be expressed as

$$D_i = k_i D_r, \tag{3}$$

where D_1 to D_n are the MDRs at a given wind speed for damage curves C_1 to C_n, respectively, and D_r is the MDR at a given wind speed for a reference damage curve C_r. Note that as per the assumptions, the ratio k_i is similar for the two regions. Substituting the above values in Eq. (2) for the unknown curves (say for country Y) and rearranging terms we arrive at the following expressions:

$$k_1 D_r w_1 + \cdots + D_r w_r + \cdots + k_n D_r w_n = D_g \sum_{i=1}^{n} w_i. \tag{4}$$

Thus,

$$D_r = \frac{D_g \sum_{i=1}^{n} w_i}{\sum_{i=1}^{n} k_i w_i}. \tag{5}$$

Once D_r, the MDR for the unknown reference curve (or building class) is known, Eq. (3) can be used to find the MDRs for other building classes at a given velocity. This process is repeated for each velocity range until the damage curve for the entire velocity range is obtained for a particular building class. The derived relativities are then judged against wind engineering principles and loss observations, where available as well as modified to account for the differences in the building types of the two regions.

4. An example implementation

The disaggregation methodology described above is now applied to generate a complete set of vulnerability curves for Puerto Rico, based on a generic vulnerability curve for commercial buildings.

Data comprising of more than \$1 billion of insurance losses to residential and commercial properties, suffered by several insurance companies during Hurricane Hugo in 1989 and Hurricane Georges in 1998, in Puerto Rico, were analyzed to obtain generic vulnerability curves for residential and commercial portfolios. Fig. 3, based on an analysis of the data shows the generic vulnerability curve for commercial buildings in Puerto Rico. The methodology described above will be used for disaggregating the generic curve into building classes present in Puerto Rico commercial building stock as shown in Table 1. Table 1 is based on data pertaining to the insured exposure in Puerto Rico representative of the loss data. Note that in Table 1, low-rise buildings are of 1–3 story height, mid-rise of 4–7 stories and buildings with 8 stories or more are termed as high-rise.

In order to apply the above methodology, vulnerability curves for another region or country, to be used as benchmark curves, are required. Fig. 4 shows the benchmark hurricane vulnerability curves, based on analyses of insurance claims data (as explained in Section 2), for a sample of commercial building classes. The methodology uses these relative vulnerabilities and combines them with the generic vulnerability of commercial buildings in Puerto Rico (Fig. 3), while weighting them with the inventory mix (Table 1) to obtain the vulnerability curves for various commercial building classes present in Puerto Rico.

Fig. 5 shows the disaggregated vulnerability curves for Puerto Rico along with the generic vulnerability curve. A comparison between Figs. 4 and 5 shows that while the Puerto Rico vulnerability curves (Fig. 5) have in general retained the relative

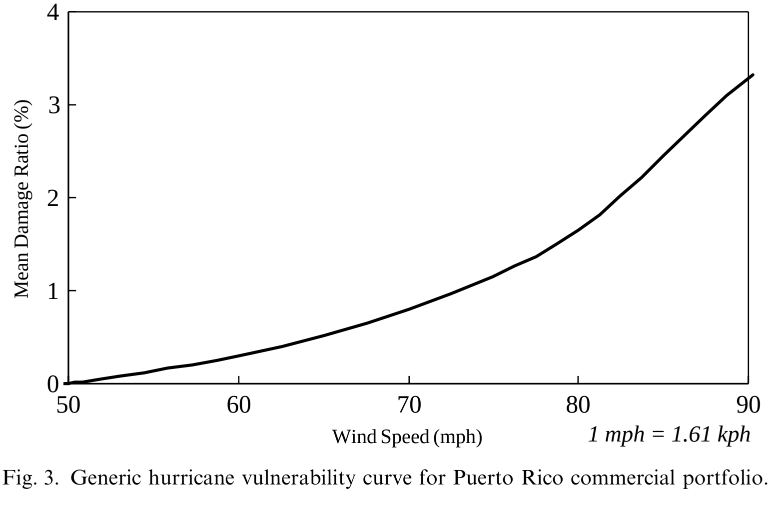

Fig. 3. Generic hurricane vulnerability curve for Puerto Rico commercial portfolio.

Table 1
Puerto Rico commercial building inventory

Building material	Percentage present		
	Low rise	Mid rise	High rise
Wood	0.5	0.0	0.0
Masonry	18.0	0.0	0.0
Reinforced concrete	31.5	12.0	8.0
Steel frame/light metal	18.0	8.0	4.0

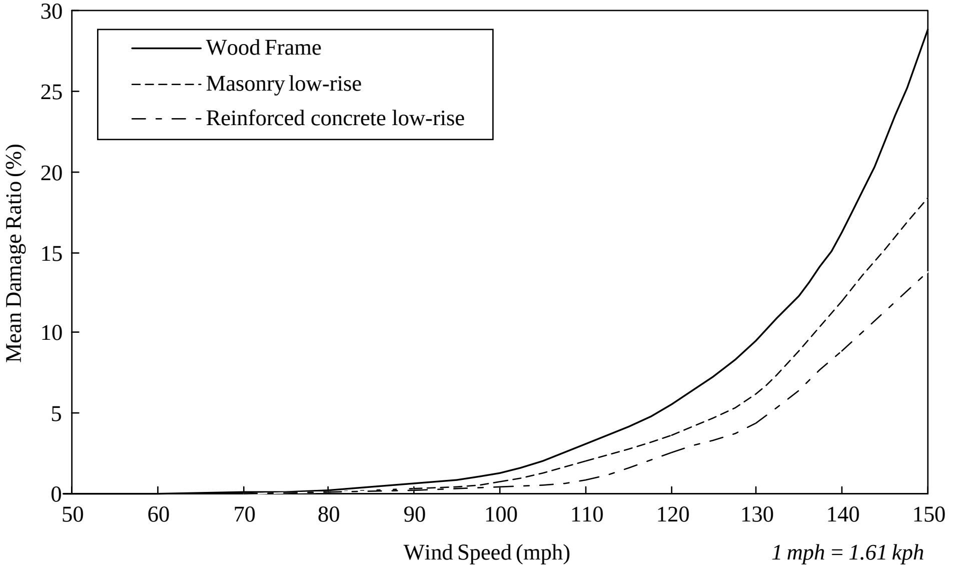

Fig. 4. Benchmark hurricane vulnerability curves for commercial building classes.

vulnerabilities of the curves shown in Fig. 4, they are somewhat steeper, especially at the lower wind speed range. This increase in vulnerability is attributed to the uniqueness of the generic vulnerability curve for Puerto Rico as well as the properties of the commercial building inventory of the region.

5. Hurricane loss estimation

Hurricane risk models typically used by the insurance industry estimate losses to their portfolio of insured property due to a set of a simulated storms derived from an existing historical record. These storm sets attempt to predict, from the short-term historical record, a reasonable representation of the frequency and intensity of storms that could make landfall at any location. Each of these storm sets is designed

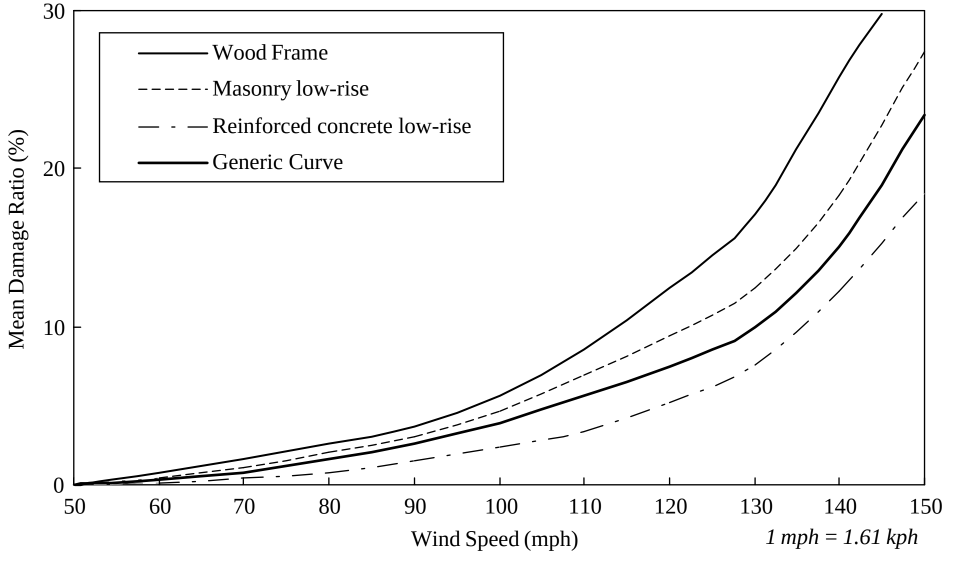

Fig. 5. Hurricane vulnerability curves for commercial building classes in Puerto Rico.

to capture details of storm size and structure that can be used to indicate the wind field at a particular location. The local wind data is then combined with vulnerability functions to yield property damage estimates.

Once the vulnerability curves for a region are developed, they are then combined with the hurricane hazard information and the insurance exposure to estimate the insurance losses at a specified location or for a region as a whole. A hurricane loss estimation model can be used in several ways, for instance, to

(a) estimate losses if past events were to occur today;
(b) estimate losses due to potential future storms of varying intensities and track.

5.1. Insurance losses for historical events using present day exposures

The vulnerability curves developed using the above methodology and the modeled windspeeds for Puerto Rico are combined with the current residential and commercial exposure in Puerto Rico to obtain losses for various historical hurricanes passing through Puerto Rico. The windspeeds at various locations in Puerto Rico are obtained using a windfield model. The main storm parameters used in windspeed calculations are central pressure, radius to maximum winds, forward velocity, storm direction and landfall location. Detailed theoretical and analytical formulations of windfield modeling are given in [8,9]. Fig. 6 shows the losses due to five major hurricanes in Puerto Rico in the 20th century as compared to losses suffered in Hurricane Georges. Hurricane Georges made landfall in Puerto Rico on September

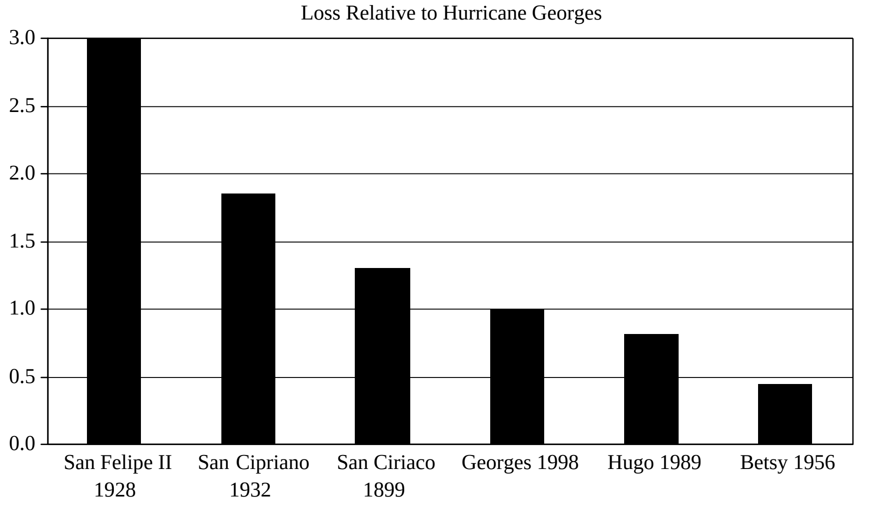

Fig. 6. A comparison of insurance losses for historical hurricanes in Puerto Rico relative to those for Hurricane Georges in 1998 with 1998 industry exposure.

21, 1998. The eye hit the east coast and followed a westward path across the center of the island, battering the island for more than 7 h before moving on to the Dominican Republic and Haiti. The figure essentially gives an idea of the relative losses to expect if a hurricane say, similar to San Felipe II of 1928 were to strike Puerto Rico today.

5.2. *Insurance losses due to potential future storms of varying intensities and track*

Despite a significant record of hurricane activity, the direct loss experience from these historical events is not sufficient to form the basis for projecting future hurricane risk. Thus, the available databases of historical hurricanes are unable to represent a comprehensive spectrum of physically plausible events in terms of their physical characteristics, landfall locations, and probabilities. To address these challenges and provide a reliable longterm view of hurricane risk, a stochastic model, that includes a database of thousands of stochastically defined hurricanes, is developed. Each of these stochastic events is uniquely defined by its track or landfall location, its physical characteristics and its rate of occurrence. These physical characteristics are defined by the central pressure, wind profile (radius to maximum winds), track, forward velocity, rate of pressure decay, and windfield over water or land and a probability of future occurrence based upon the likelihood of the combination of the characteristics and landfall locations.

The stochastic set of storms is generated using a "random-walk" technique frequently applied to turbulent dispersion problems by considering each hurricane to be advected by a 2D "turbulent" translational velocity field superimposed on a "mean" translational velocity field. The random-walk model enables the realistic reproduction of central-pressure evolution throughout the lifetime of the track.

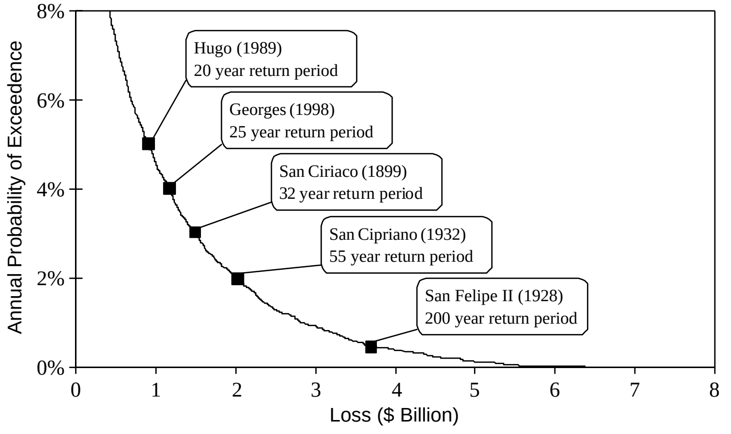

Fig. 7. Stochastic model exceeding probability loss curve for Puerto Rico with historical event comparisons (losses for all storms based on current exposed value).

Details of the development of the "random-walk" stochastic storm model are given in [10].

The modeled storms as a set estimate the full range of events that could occur in a given region. If losses for all modeled storms are analyzed, they can be sorted from largest to smallest loss. Each storm is assigned an annual probability of exceedance based on overall event rates in a given region and the modeled storm physical characteristics. This is done on an event-by-event basis by calculating the probability that at least one event occurs generating more loss than the loss for that particular event. This process is carried out for all events and an "exceeding probability curve" is constructed by plotting the estimated loss against the exceeding probability. The exceeding probability curve quantifies the annual probability of exceeding different loss levels in a given year. Fig. 7 shows such an exceeding probability curve for Puerto Rico. Included on the graph are a set of significant historical storms. Based on the losses due to a historic storm, an equivalent return period for that loss can be calculated from the modeled exceeding probability curve as indicated. For example, losses equivalent to or greater than those produced by Hurricane Georges have a return period of 25 years.

6. Conclusions

The assessment of vulnerability of buildings to windstorms has been discussed. A methodology for the disaggregation of a generic vulnerability curve into several curves that cover various range of building classes has been developed. The methodology disaggregates the generic vulnerability curve of a particular region based on loss data and the building inventory of the region as well as the relative building vulnerabilities of various building classes of another known region. The methodology can provide a quick estimate of the detailed building vulnerabilities for a region with minimum available information.

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